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J/ψ elliptic flow in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

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Abstract

We report a precise measurement of the J/ψ elliptic flow in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE detector at the LHC. The J/ψ mesons are reconstructed at mid-rapidity ($|y| < 0.9$) in the dielectron decay channel and at forward rapidity ($2.5 < y < 4.0$) in the dimuon channel, both down to zero transverse momentum. At forward rapidity, the elliptic flow v_2 of the J/ψ is studied as a function of transverse momentum and centrality. A positive v_2 is observed in the transverse momentum range $2 < p_{\rm T} < 8$ GeV/c in the three centrality classes studied and confirms with higher statistics our earlier results at $\sqrt{s_{\rm NN}} = 2.76$ TeV in semi-central collisions. At mid-rapidity, the J/ψ v_2 is investigated as a function of transverse momentum in semi-central collisions and found to be in agreement with the measurements at forward rapidity. These results are compared to transport model calculations. The comparison supports the idea that at low $p_{\rm T}$ the elliptic flow of the J/ψ originates from the thermalization of charm quarks in the deconfined medium, but suggests that additional mechanisms might be missing in the models.

*See Appendix A for the list of collaboration members

Extreme conditions of temperature and pressure created in ultra-relativistic heavy-ion collisions enable exploration of the phase diagram region where Quantum Chromodynamics (QCD) predicts the existence of a deconfined state, the Quark-Gluon Plasma (QGP) [1, 2]. Heavy quarks are produced through hard-scattering processes prior to the formation of the QGP and experience the evolution through interactions in the medium. Therefore, the measurement of bound states of heavy quarks, such as the J/ψ, is expected to provide sensitive probes of the strongly-interacting medium [3]. Theoretical calculations based on lattice QCD predict a J/ψ suppression to be induced by the screening of the color force in a deconfined medium which becomes stronger as the temperature increases [4, 5]. In a complementary way to this static approach, J/ψ suppression can be also interpreted as the result of dynamical interactions with the surrounding partons [6–8]. Within these scenarios, the J/ψ suppression, experimentally quantified via the nuclear modification factor, $R_{\rm AA}$ (the ratio between the yields in Pb–Pb to pp collisions normalised by the number of nucleon-nucleon collisions), is expected to become stronger (smaller $R_{\rm AA}$) with higher initial temperatures of the QGP, hence with higher collision energies. However, the $R_{\rm AA}$ of inclusive [1] J/ψ with transverse momentum $p_{\rm T} < 8$ GeV/c observed by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [9] and $\sqrt{s_{\rm NN}} = 5.02$ TeV [10] is larger than what has been measured at lower energies at the Relativistic Heavy Ion Collider (RHIC) [11–14] and exhibits almost no centrality dependence. Furthermore, in central collisions the measured $R_{\rm AA}$ values decrease from low to high $p_{\rm T}$ [15, 16]. The J/ψ $R_{\rm AA}$ enhancement from RHIC to LHC energies can be explained by theoretical models [6–8, 17–19] which include a dominant contribution from J/ψ (re)generation through (re)combination of thermalized charm quarks in the medium, during or at the phase boundary of the deconfined phase [2].

Additional observables are required to better constrain theoretical models and study the interplay between suppression and regeneration mechanisms [20]. The azimuthal anisotropy of the final-state particle momentum distribution is sensitive to the geometry and the dynamics of the early stages of the collisions. The spatial anisotropy in the initial matter distribution due to the nuclear overlap region in non-central collisions is transferred to the final momentum distribution via multiple collisions in a strongly coupled system [21]. The beam axis and the impact parameter vector of the colliding nuclei define the reaction plane. The second coefficient (v_2) of the Fourier expansion of the final state particle azimuthal distribution with respect to the reaction plane is called elliptic flow.

Within the transport model scenario [7, 19], (re)generated J/ψ inherit the flow of the (re)combined charm quarks. If charm quarks do thermalize in the QGP, then (re)generated J/ψ can exhibit a large elliptic flow. In contrast, only a small azimuthal anisotropy, due to the shorter in-plane versus out-of-plane pathlength, is predicted for the surviving primordial J/ψ. The ALICE and CMS collaboration have measured a positive elliptic flow of D mesons in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [22, 23]. The comparison of J/ψ and D-meson v_2 could help to constrain the dynamics of charm quarks in the medium and the theoretical model calculations [24–26].

At RHIC, the STAR Collaboration measured, in Au–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV, a J/ψ v_2 consistent with zero, albeit with large uncertainties [27]. At the LHC a first indication of positive J/ψ v_2 was observed by the ALICE Collaboration in semi-central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with a 2.7σ significance for inclusive J/ψ with $2 < p_{\rm T} < 6$ GeV/c at forward rapidity [28]. The CMS Collaboration also reported a positive v_2 for prompt J/ψ at high $p_{\rm T}$ and mid-rapidity [29]. A precision measurement of the J/ψ v_2 in Pb–Pb collisions at the highest LHC energy will provide valuable insights on the J/ψ production mechanisms and on the thermalization of charm quarks. Indeed, the higher energy density of the medium should favor charm quark thermalization, and thus increase its flow. In addition, the larger number of produced $c\bar{c}$ pairs should increase the fraction of J/ψ formed by regeneration

[1] Inclusive J/ψ include prompt J/ψ (direct and decays from higher mass charmonium states) and non-prompt J/ψ (feed down from b-hadron decays). In this Letter, all J/ψ measurements refer to inclusive J/ψ production unless otherwise stated.

[2] The terms (re)generation and (re)combination denote the two possible mechanisms of J/ψ generation by combination of charm quarks at the QGP phase boundary and the continuous dissociation and recombination of charm quarks during the QGP evolution.

mechanisms, both leading to an increase of the observed J/ψ v_2.

In this Letter, we report ALICE results on inclusive J/ψ elliptic flow in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for two rapidity ranges. At forward rapidity ($2.5 < y < 4.0$) the J/ψ are measured via the $\mu^+\mu^-$ decay channel and at mid-rapidity ($|y| < 0.9$) via the e^+e^- decay channel. The results are presented as a function of $p_{\rm T}$ in the range $0 < p_{\rm T} < 12$ GeV/c. For the dimuon channel different collision centralities are also investigated.

The ALICE detector is described in [30]. At forward rapidity the production of quarkonia is measured with the muon spectrometer [3] consisting of a front absorber stopping the hadrons followed by five tracking stations comprising two planes of cathode pad chambers each, with the third station inside a dipole magnet. The tracking apparatus is completed by a triggering system made of four planes of resistive plate chambers downstream of an iron wall. At mid-rapidity quarkonium production is measured with the central barrel detectors [31]. Tracking within $|\eta| < 0.9$ is performed by the Inner Tracking System (ITS) [32] and the Time Projection Chamber (TPC) [33]. The specific ionization energy loss (d$E/$dx) in the gas of the TPC is used for particle identification (PID). In addition the Silicon Pixel Detector (SPD) is used to locate the interaction point. The SPD corresponds to the two innermost layers of the ITS covering respectively $|\eta| < 2.0$ and $|\eta| < 1.4$. The V0 counters [34], consisting of two arrays of 32 scintillator sectors each covering $2.8 \leq \eta \leq 5.1$ (V0-A) and $-3.7 \leq \eta \leq -1.7$ (V0-C), are used as trigger and centrality detectors [35, 36]. As described later, the SPD, TPC, V0-A, and V0-C are also used as event plane detectors. All of these detectors have full azimuthal coverage.

The data were collected in 2015. The analysis at mid-rapidity uses minimum bias (MB) Pb–Pb collisions. The MB trigger requires a signal in both V0-A and V0-C and is fully efficient for the centrality range 0–90%. At forward rapidity, the analysis uses opposite-sign dimuon (MU) triggered Pb–Pb collisions. The MU trigger requires a MB trigger and at least a pair of opposite-sign track segments in the muon trigger system, each with a $p_{\rm T}$ above the threshold of the on-line trigger algorithm, set to provide 50% efficiency for muon tracks with $p_{\rm T} = 1$ GeV/c. The beam-induced background was further reduced offline using the V0 and the zero degree calorimeter (ZDC) timing information. The contribution from electromagnetic processes was removed by requiring a minimum energy deposited in the neutron ZDCs [37]. The resulting data samples correspond to integrated luminosities of about 13 μb^{-1} and 225 μb^{-1} at mid- and forward rapidity, respectively.

J/ψ candidates are formed by combining pairs of opposite-sign tracks reconstructed in the geometrical acceptance of the muon spectrometer or central barrel. The reconstructed tracks in the muon tracker are required to match a track segment in the muon trigger system above the aforementioned $p_{\rm T}$ threshold. At mid-rapidity the tracks must pass a $p_{\rm T}$ cut of 1 GeV/c and an electron selection criterion based on the expected d$E/$dx [33].

The dimuon v_2 is calculated using event plane (EP) based methods. The angle of the reaction plane of the collision is estimated, event by event, by the second harmonic EP angle Ψ [38], which is obtained from the azimuthal distribution of reconstructed tracks in the TPC or track segments in the SPD for the mid- and forward rapidity analyses, respectively. Effects of non-uniform acceptance in the EP determination are corrected using the methods described in [39]. At mid-rapidity, the EP was calculated for each electron pair subtracting the contribution of the pair tracks to remove auto-correlations.

The J/ψ $p_{\rm T}$ results were obtained, as proposed in [40], by fitting the distribution of $v_2 = \langle \cos 2(\varphi - \Psi) \rangle$ versus the invariant mass ($m_{\ell\ell}$) of the dilepton pair, with φ being its azimuthal angle. The total flow $v_2(m_{\ell\ell})$ is the combination of the signal and the background flow and can be expressed as

[3] In the ALICE reference frame, the muon spectrometer covers a negative η range and consequently a negative y range. We have chosen to present our results with a positive y notation, due to the symmetry of the collision system.

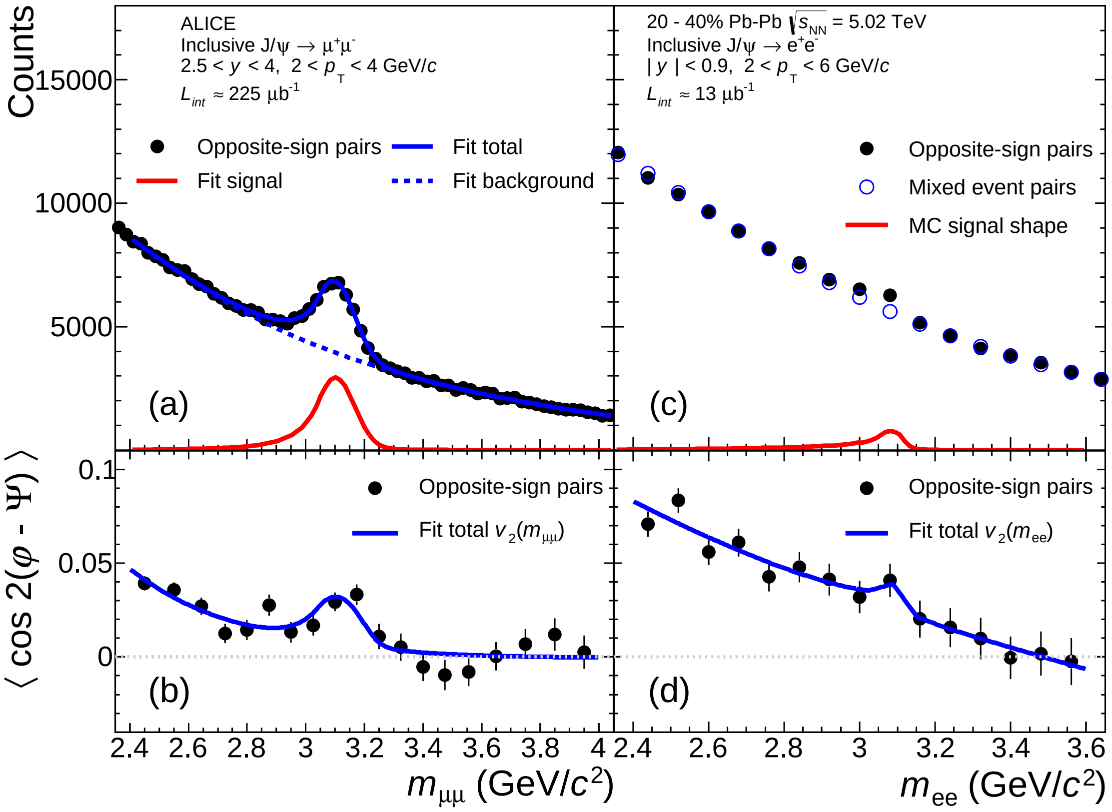

Fig. 1: (color online) Invariant mass distribution (top) and $\langle \cos 2(\varphi - \Psi) \rangle$ as a function of $m_{\ell\ell}$ (bottom) of opposite-sign dimuons (left) with $2 < p_{\rm T} < 4$ GeV/c and $2.5 < y < 4$ and dielectrons (right) with $2 < p_{\rm T} < 6$ GeV/c and $|y| < 0.9$, in semi-central (20–40%) Pb–Pb collisions.

$$v_2(m_{\ell\ell}) = v_2^{\rm sig}\alpha(m_{\ell\ell}) + v_2^{\rm bkg}(m_{\ell\ell})[1 - \alpha(m_{\ell\ell})], \tag{1}$$

where $v_2^{\rm sig}$ and $v_2^{\rm bkg}$ are the elliptic flow of the J/ψ signal (S) and of the background (B), respectively (see bottom panels of Fig. 1). The signal fraction $\alpha(m_{\ell\ell}) = S(m_{\ell\ell})/(S(m_{\ell\ell}) + B(m_{\ell\ell}))$ was extracted from fits to the invariant mass distribution (see top panels of Fig. 1) in each $p_{\rm T}$ and centrality class.

At forward rapidity, the J/ψ peak (S-term of $\alpha(m_{\ell\ell})$) is fit with an extended Crystal Ball function or a pseudo-Gaussian, both composed of a Gaussian core with non-Gaussian tails [41]. The underlying continuum (B-term of $\alpha(m_{\ell\ell})$) is described with the ratio of second- to third-order polynomials, a pseudo-Gaussian with a width quadratically varying with mass, or Chebyshev polynomials of order six. The background flow $v_2^{\rm bkg}$ was parametrized using a second-order polynomial, a Chebyshev polynomial of order four, or the product of a first order polynomial and an exponential function. At mid rapidity, the underlying continuum was estimated combining opposite-sign electrons from different events (using an event-mixing technique) or combining same-sign electrons from the same event. After removing the underlying continuum, the J/ψ signal was obtained by counting the number of dielectrons or from a fit with a MC-generated shape. The background flow was parametrized using a second-, third- or fifth-order polynomial depending on the $p_{\rm T}$ class. Additionally, the PID and track-quality selection criteria were varied as part of the systematic uncertainty evaluation.

The J/ψ v_2 and its statistical uncertainty in each $p_{\rm T}$ and centrality class were determined as the average of the $v_2^{\rm sig}$ obtained by fitting $v_2(m_{\ell\ell})$ using Eq. 1 with the various $\alpha(m_{\ell\ell})$ and $v_2^{\rm bkg}(m_{\ell\ell})$ parametrizations in several invariant mass ranges, while the corresponding systematic uncertainties were defined as the RMS of these results. A similar method was used to extract the uncorrected (for detector acceptance and efficiency) average transverse momentum of the reconstructed J/ψ in each centrality and $p_{\rm T}$ class, which is used to locate the data points when plotted as a function of $p_{\rm T}$. Consistent v_2 values were obtained using an alternative method [38] in which the J/ψ raw yield is extracted, as described before, in bins of $(\varphi - \Psi)$ and $p_{\rm T}$ is evaluated by fitting the data with the function $\frac{dN}{d(\varphi-\Psi)} = A[1 + 2v_2 \cos 2(\varphi - \Psi)]$, where A is a normalization constant.

Non-flow effects (J/ψ-EP correlations not related to the the initial geometry symmetry plane, such as higher-mass particle decays or jets) were estimated to be small with respect to the other uncertainties by repeating the analysis at forward rapidity using the EP determined in either V0-A ($\Delta\eta = 5.3$) or V0-C (no η gap) detector.

The finite resolution in the EP determination smears out the azimuthal distributions and lowers the value of the measured anisotropy [38]. The SPD- and TPC-based EP resolutions were determined by applying the 3 sub-event method [38]. For the SPD (TPC), the 3 sub-events were obtained using V0-A, V0-C and SPD, with $\Delta\eta_{\rm V0A-SPD} = 1.4$ ($\Delta\eta_{\rm V0A-TPC} = 1.9$), $\Delta\eta_{\rm V0A-V0C} = 4.5$ and $\Delta\eta_{\rm SPD-V0C} = 0.3$ ($\Delta\eta_{\rm TPC-V0C} = 0.8$) pseudo-rapidity gaps. A systematic uncertainty of 1% on the EP determination was estimated exploiting the availability of different sub-events, built from the multiplicity measurement in the V0-A or V0-C, track segments in the SPD, and tracks in the TPC. The EP resolution for each wide centrality class was calculated as the average of the values obtained in finer classes weighted by the number of reconstructed J/ψ. Table 1 shows the corresponding resolution for each centrality class, applied to the forward rapidity results. For the mid-rapidity result, the TPC EP resolution is 0.880 ± 0.009 (syst) in the centrality class 20–40%.

Centrality	$\langle N_{\rm part}\rangle$	EP resolution
5–20%	287 ± 4	0.873 ± 0.009
20–40%	160 ± 3	0.910 ± 0.009
40–60%	70 ± 2	0.832 ± 0.008

Table 1: Average number of participants $\langle N_{\rm part}\rangle$ and SPD EP resolution for each centrality class (expressed in percentage of the nuclear cross section) [36]. The quoted uncertainties are systematic.

At forward rapidity, the J/ψ reconstruction efficiency depends on the detector occupancy, which could bias the v_2 measurement. This effect was evaluated by embedding azimuthally isotropic simulated decays into real events. The resulting v_2 does not deviate from zero by more than 0.006 in the centrality and $p_{\rm T}$ classes considered. This value is used as a conservative systematic uncertainty on all measured v_2 values.

Figure 2 shows J/ψ $v_2(p_{\rm T})$ at forward and mid-rapidity in semi-central (20–40%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The $p_{\rm T}$ ranges are 0–2, 2–4, 4–6, 6–8, and 8–12 GeV/c and 0–2, 2–6, and 4–12 GeV/c at forward and mid-rapidity, respectively. The vertical bars indicate the statistical uncertainties, while the boxes indicate the uncorrelated systematic uncertainties. The global relative systematic uncertainty on the EP resolution is 1.0% and is correlated with $p_{\rm T}$. At forward rapidity, a positive v_2 is observed for semi-central collisions (20–40%). Including statistical and systematic uncertainties the significance of a non-zero v_2 is as large as 6.6σ in the $p_{\rm T}$ class 4–6 GeV/c. The J/ψ v_2 increases with $p_{\rm T}$ up to $v_2 = 0.113 \pm 0.015({\rm stat}) \pm 0.008({\rm syst})$ at $4 < p_{\rm T} < 6$ GeV/c. The J/ψ $v_2(p_{\rm T})$ at mid-rapidity is similar to that at forward rapidity, albeit with large uncertainties. At mid-rapidity, the J/ψ v_2 in the range $2 < p_{\rm T} < 6$ GeV/c is $v_2 = 0.129 \pm 0.080({\rm stat}) \pm 0.040({\rm syst})$.

Transport model calculations including a large J/ψ (re)generation component (about 50% for semi-central collisions) from deconfined charm quarks in the medium [8, 25, 42] are also shown in Fig. 2. In the model by Du *et al.* [25] (TM1) the v_2 of inclusive J/ψ (hashed and double-hashed bands at forward and mid-rapidity) has three origins. First, thermalized charm quarks in the medium transfer a significant elliptic flow to (re)generated J/ψ. Second, primordial J/ψ traverse a longer path through the

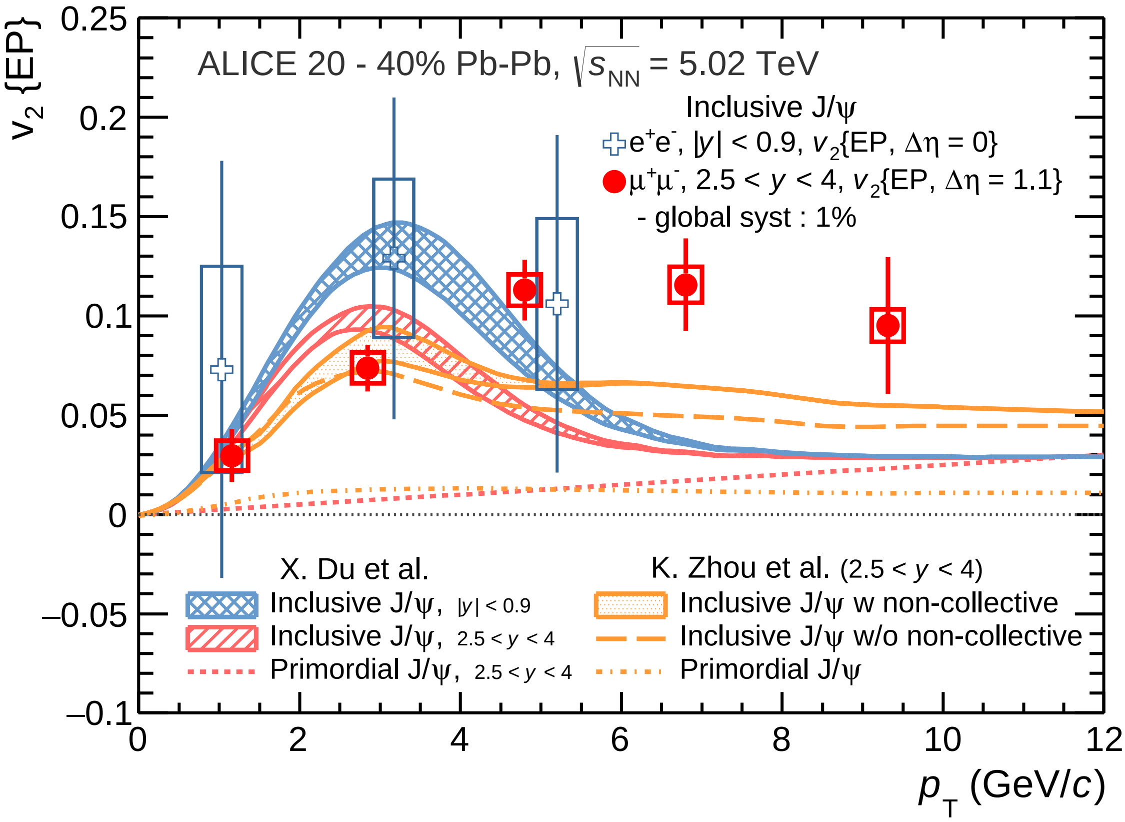

Fig. 2: (color online) Inclusive J/ψ $v_2(p_{\rm T})$ at forward and mid-rapidity for semi-central (20–40%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Calculations from transports model by [25] and [8] are also shown.

medium when emitted out-of-plane than in-plane resulting in a small apparent v_2 (pair dissociation by interactions with the surrounding color charges). Third, when the b quarks thermalize their flow will be transferred to b-hadrons at hadronization and to non-prompt J/ψ from the b-hadron decay. The second component (survival provability of primordial J/ψ) is represented as a short-dashed line to highlight the small J/ψ v_2 in the absence of heavy-quark collective flow. The model by Zhou *et al.* [8] (TM2) includes an additional non-collective J/ψ v_2 component, which arises from the modification of the quarkonium production in the presence of a strong magnetic field in the early stage of the heavy-ion collision [43]. The calculations of TM2 are shown at forward rapidity with (shaded band) and without (long-dashed line) the non-collective J/ψ v_2 component. As for TM1, the v_2 resulting from the different in-plane than out-of-plane survival probability of primordial J/ψ is shown as a dash-dotted line.

TM1 [25] is able to describe qualitatively the J/ψ $R_{\rm AA}$ measurements by ALICE reported in [10]. The model also agrees with ALICE J/ψ v_2 measurements at forward rapidity at $\sqrt{s_{\rm NN}} = 2.76$ TeV [28] and at mid-rapidity at $\sqrt{s_{\rm NN}} = 5.02$ TeV. However, at high $p_{\rm T}$ ($p_{\rm T} > 4$ GeV/c), clear discrepancies are observed between the model and the J/ψ v_2 at forward rapidity and $\sqrt{s_{\rm NN}} = 5.02$ TeV. Some tension is also seen between the calculations of this model and the $R_{\rm AA}$ measurement by ALICE in this higher $p_{\rm T}$ range in [10]. At lower $p_{\rm T}$ the model reproduces the magnitude of the measurement by a dominant contribution of J/ψ elliptic flow inherited from thermalized charm quarks. However, the overall shape of the $v_2(p_{\rm T})$ is missed and the v_2 at high $p_{\rm T}$ is underestimated. This disagreement suggests a missing mechanism in the model. Similar conclusions can be derived from the comparison to TM2 [8]. The addition of the v_2 arising from a possible strong magnetic field in the early stage of heavy-ion collisions [43] improves the comparison with the measured J/ψ v_2 at forward rapidity, especially at high $p_{\rm T}$. Such non-collective component was able to reproduce the prompt J/ψ v_2 at high $p_{\rm T}$ measured by CMS in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [29].

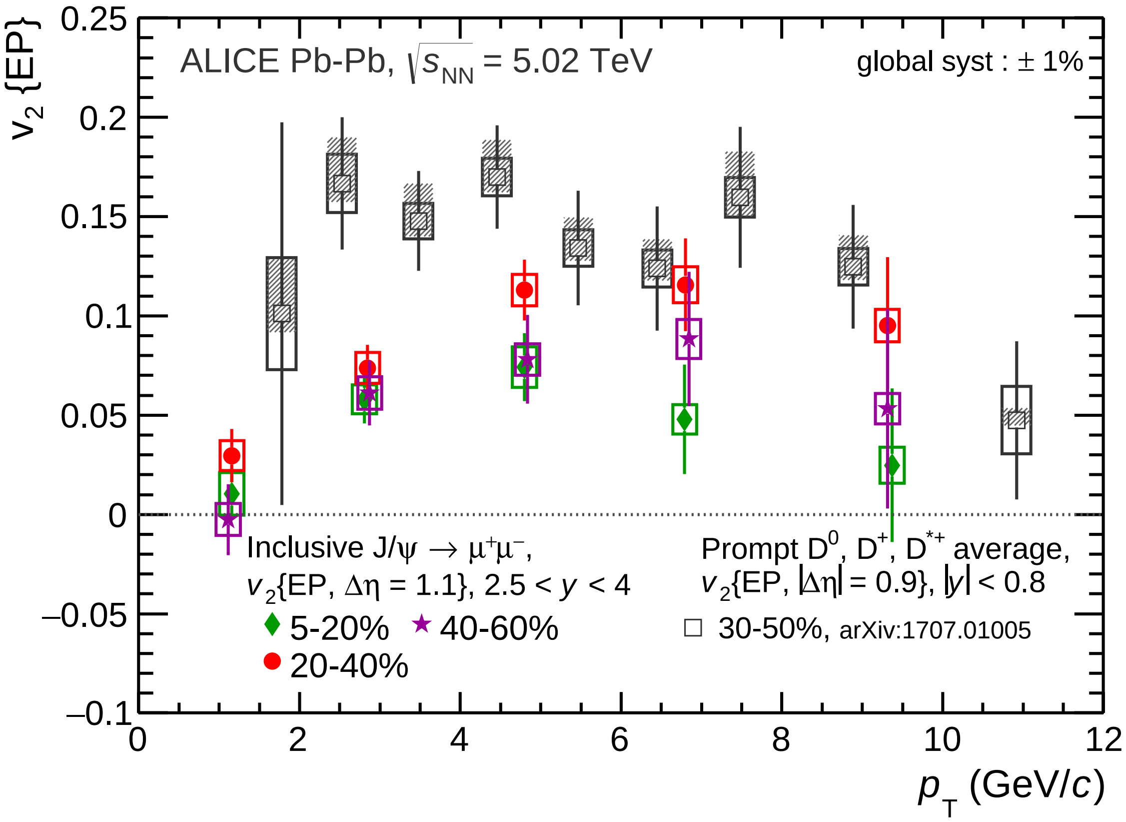

Fig. 3: (color online) Inclusive J/ψ $v_2(p_{\rm T})$ at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for three centrality classes, 5–20%, 20–40%, and 40–60%. The average of $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$ $v_2(p_{\rm T})$ at mid-y in the centrality class 30–50% is also shown for comparison [22].

Figure 3 presents the $p_{\rm T}$ dependence of the J/ψ v_2 at forward rapidity for three centrality classes, 5–20%, 20–40%, and 40–60%. As in semi-central (20–40%) collisions, a significant v_2 is also observed for J/ψ with $2 < p_{\rm T} < 8$ GeV/c in the 5–20% and 40–60% centrality classes. The $p_{\rm T}$ dependence of the J/ψ v_2 at forward rapidity is consistent within uncertainties in the three centrality classes presented here. The J/ψ $v_2(p_{\rm T})$ appears to be maximum for the 20–40% centrality class and tends to decrease for more central or peripheral collisions. Interestingly, for identified light hadrons in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, the $v_2(p_{\rm T})$ is maximum in the 40–60% centrality class and decreases for more central collisions [44]. This different behavior could be understood in the framework of transport models by the increasing contribution of J/ψ regeneration for more central collisions [25, 42].

Also shown in Fig. 3 is the $v_2(p_{\rm T})$ of prompt D-mesons in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for the 30–50% centrality class measured by ALICE at mid-rapidity [22]. The vertical bars indicate the statistical uncertainties, the open boxes the uncorrelated systematic uncertainties and the shaded boxes the feed-down uncertainties. Although the centrality and rapidity ranges are different, it is clear that at low $p_{\rm T}$ ($p_{\rm T} < 4$ GeV/c) the v_2 of D mesons is higher than that of J/ψ mesons. The large values of the measured v_2 of both D and J/ψ mesons support the conclusion that both D and J/ψ mesons inherit their flow from thermalized charm quarks.

In summary, we report the ALICE measurements of inclusive J/ψ elliptic flow at forward and mid-rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. At forward rapidity, the $p_{\rm T}$ dependence of the J/ψ v_2 was measured in the 5–20%, 20–40%, and 40–60% centrality classes for $p_{\rm T} < 12$ GeV/c. For all the reported centrality classes a significant J/ψ v_2 signal is observed in the intermediate region $2 < p_{\rm T} < 8$ GeV/c. The results unambiguously establish for the first time that J/ψ mesons exhibit collective flow. At mid-rapidity, the $p_{\rm T}$ dependence of the J/ψ v_2 was measured in semi-central 20–40% collisions and is found to be similar to the measurement at forward rapidity, albeit with larger uncertainties. At high $p_{\rm T}$, transport models underestimate the measured J/ψ v_2. The origin of such discrepancy is currently not understood and suggests a missing mechanism in the models. At low $p_{\rm T}$, the magnitude of the observed v_2 is achieved within transport models implementing a strong J/ψ (re)generation component from (re)combination of thermalized charm quarks in the QGP. Thus, the measurement of the J/ψ elliptic flow combined with the $R_{\rm AA}$ provides substantial evidence for thermalized charm quarks and (re)generation of J/ψ.

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